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6. AUTHOR(S)
Biswanath Mukherjee
(Principal Investigator)

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of California, Davis
Division of Computer Science
Davis, CA 95616

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The main focus of this project was on high-speed fiber-optic local and metropolitan area networks (LANs/MANs) which cover larger distances than traditional LANs, are implemented in fiber, and operate at high data rates (100 Mbps – 1 Gbps range). Considerable progress has been made on the investigation of new medium access control techniques which can not only provide good delay and throughput characteristics, but also provide fairness, support scalability, and accommodate integrated services. Research on the next generation of local networks (referred to as local lightwave networks) was also initiated, with the goal being to exploit the huge electro-optic bandwidth mismatch by employing innovative parallelism and concurrency mechanisms, viz. wavelength division multiplexing (WDM). Progress has been made on the development of new architectures and protocols suitable for lightwave technology.

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INTELLIGENT, INTEGRATED FIBER OPTIC NETWORKS

Final Technical Report

Covering the period March 1, 1989 to August 31, 1992

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Biswanath Mukherjee
Principal Investigator

Division of Computer Science
University of California
Davis, CA 95616
Tel: (916) 752-4826
FAX: (916) 752-4767
E-mail: mukherje@cs.ucdavis.edu

October 29, 1992

ABSTRACT

The main focus of this project was on high-speed fiber-optic local and metropolitan area networks (LANs/MANs) which cover larger distances than traditional LANs, are implemented in fiber, and operate at high data rates (100 Mbps – 1 Gbps range). Considerable progress has been made on the investigation of new medium access control techniques which can not only provide good delay and throughput characteristics, but also provide fairness, support scalability, and accommodate integrated services. Research on the next generation of local networks (referred to as local lightwave networks) was also initiated, with the goal being to exploit the huge electro-optic bandwidth mismatch by employing innovative parallelism and concurrency mechanisms, viz. wavelength division multiplexing (WDM). Progress has been made on the development of new architectures and protocols suitable for lightwave technology.

I. INTRODUCTION: Target Network Environment – Second Generation (Fiber Optic) LANs

The first generation of local area networks (LANs), e.g., Ethernet and token ring, are in wide deployment today. Second generation LANs, also referred to as high-speed LANs and as metropolitan area networks (MANs) (since they cover larger distances than earlier LANs), are being implemented in fiber and operate at high data rates (100 Mbps – 1 Gbps range). The main difference in characteristic of such fiber optic networks is that they need to carry information unidirectionally. Hence, under this project, we investigated the capabilities of the *folded* unidirectional bus and the *dual* unidirectional bus structures for application in second generation LANs, and we developed corresponding medium access control protocols for such networks.

Specifically, we have investigated the capabilities of a simple protocol, called the p_i-persistent protocol. Other competing protocols for second generation LANs are the Fiber Distributed Data Interface (FDDI) and the IEEE 802.6 (DQDB) protocols. We remark that our protocol is highly competitive and advantageous since (1) FDDI suffers from scalability problems (viz. when the data rate or the distance

spanned by the network increases, its throughput decreases); (2) DQDB suffers from fairness problems (i.e., service received by stations are position dependent); while (3) our proposals suffer from neither problem.

We have also conducted research on adaptive protocols, which properly adjust the network operating parameters in real time based on prevailing network traffic conditions based on feedback from the broadcast medium. Also, we have investigated mechanisms to integrate multi-media traffic on fiber optic LANs.

Finally, we have also initiated research on third-generation LANs and MANs which are designed to exploit the huge electro-optic bandwidth mismatch by employing innovative parallelism and concurrency mechanisms. Specifically, a technique called wavelength-division multiplexing (WDM) is employed to support numerous parallel channels on the same fiber with each channel operating at peak electronic speed, and corresponding new network architectures and protocols have been investigated.

Our research contributions are briefly summarized below. Please see the referenced technical papers and PhD dissertations for additional details.

II. SUMMARY OF ACCOMPLISHMENTS

A. Probabilistic Scheduling and Fairness in Medium Access Control Protocols

A sound protocol design must have the following characteristics:

(1) low **delay** (response time),
(2) high **throughput** (ideally full channel capacity must be utilized to carry information),
(3) provide **fairness** in performance, and
(4) allow **scalability** (in number of users, channel data rate, and geographical coverage).

Low delay and high throughput are addressed in most network designs, but **fairness** is a new and major issue that arises because of the fiber optic medium's **unidirectionality** property, which introduces an inherent asymmetry in the system. Questions that arise are: (1) should a station be allowed to hog all or most of the bandwidth? (2) shouldn't two stations with identical characteristics but different positions on the network receive identical service? and (3) how can the available bandwidth be divided among the stations so that this division is fair? (In general, there can be a number of ways fairness can be defined.) Also desirable are network protocols which are **scalable**.

Our approach to providing both fairness and scalability (besides the low delay and high throughput requirements) has been via the design and development of a probabilistic scheduling strategy, called the p_i-persistent protocol. Under this scheme, stations are sensitive towards the existence of their peers, and they leave some of the bandwidth unused for the other stations, bandwidth which they could have otherwise utilized if they were "greedy". By properly controlling the fraction of bandwidth that they do not use, stations can essentially achieve fairness. Under the basic p_i-persistent protocol, time is slotted and a slot duration equals a packet's transmission time. Any station i, if it has a packet to send, checks if the slot arriving at its interface is empty or not. If the slot is empty, station i transmits its packet in the empty slot with probability p_i. By proper choice of the set of transmission probabilities $\{p_i\}$, fairness can be achieved. The main problem is, therefore, to determine these probabilities.

We have studied this protocol's application to the following: (1) single-bus networks; (2) dual-bus networks; (3) realistic dynamic traffic environments, i.e., we have developed and studied the properties of an algorithm under which each station locally employs feedback from the (broadcast) channel to learn about newly-added stations and about changes in the other stations' traffic rates in order to adjust its own control parameter at the proper level (for fairness); (4) networks that allow slot reuse (spatial reuse of the channel bandwidth, based on destination release of slots, to further improve the network throughput); and (5) the IEEE 802.6 DQDB network to improve its fairness performance. In fact, an idle capacity scheme similar to our probabilistic scheduling concept is a feature of the IEEE 802.6 standard – in order to improve the IEEE 802.6 network's fairness performance.

The above results are published in the following papers:

[A1] B. Mukherjee and J. S. Meditch, "The p_i-persistent protocol for unidirectional broadcast bus networks," *IEEE Transactions on Communications*, vol. COM-36, pp. 1277-1286, Dec. 1988.

[A2] B. Mukherjee, "Performance of a dual-bus fiber optic network operating under a probabilistic scheduling strategy," *Performance Evaluation*, vol. 12, no. 2, pp. 127-139, April 1991.

[A3] B. Mukherjee, "An algorithm for the p_i-persistent protocol for high-speed fiber optic networks," *Computer Communications*, vol. 13, pp. 387-398, Sept. 1990.

[A4] B. Mukherjee, A. C. Lantz, N. S. Matloff, and S. Banerjee, "Dynamic control and accuracy of the p_i-persistent protocol using channel feedback," *IEEE Transactions on Communications*, vol. 39, pp. 887-898, June 1991.

[A5] B. Mukherjee, "The open-ring/active-bus network structure: Access techniques and their heavy-traffic performance," *IEEE Transactions on Communications*, vol. 39, pp. 474-477, April 1991.

[A6] B. Mukherjee and S. Banerjee, "Alternative strategies for fairness in and an analytical model of DQDB networks," *Proc., IEEE INFOCOM '91*, Bal Harbour, FL, April 1991, pp. 879-888. (Also, revised version to appear in *IEEE Transactions on Computers*.)

[A7] S. Banerjee and B. Mukherjee, "An Efficient Channel-Feedback-Based Adaptive Protocol For Scheduling Variable-Length Messages On Slotted, High-Speed Fiber Optic LANs/MANs," *Proc., Winter Simulation Conference (WSC 91)*, Phoenix, AZ, pp. 731-738, Dec. 1991 **(Invited Paper)**.

[A8] B. Mukherjee and C. Bisdikian, "A journey through the DQDB network literature," to appear in *Performance Evaluation* special issue on *Performance Modeling of High-Speed Telecommunication Systems*.

B. The Continuation-Bit Approach

This approach is aimed at improving the efficiency of packet-switched networks. It is directly applicable to the second generation LAN structures, and it may be applicable to some other packet-switched environments as well. Researchers have reached consensus that high-speed packet-switched networks must carry information via fixed-length packets, as evidenced, for example, by the IEEE 802.6 and Broadband ISDN standardization efforts. However, repeating the addressing mechanism in *every* packet also introduces a significant amount of overhead, and this an cause a corresponding loss of channel efficiency, especially for long messages (e.g., file transfers). To overcome this problem and to improve the protocol's efficiency, we have developed the **continuation-bit approach** under which the full addressing information is provided in only the *first* packet of a long message, but all subsequent packets of the message

contain minimal control information – at the very least, a single bit per packet is employed to indicate that these are continuation packets. Since the fiber optic medium is unidirectional, it turns that, even though packets from several sources can be interleaved, the entire messages can be easily reconstructed by using a stack mechanism at the destination.

We have studied this mechanism's application to (1) our p_i-persistent protocol and (2) the IEEE 802.6 protocol. The application to the IEEE 802.6 network has been integrated with the slot reuse and the fairness approaches as well, and the integrated protocol exhibits remarkable improvements in throughput and fairness. These contributions can be found in the following reports:

[B1] B. Mukherjee and A. E. Kamal, "Scheduling variable-length messages on slotted high-speed fiber optic LANs/MANs using the continuation-bit approach," *Proc., IEEE INFOCOM '91*, Bal Harbour, FL, April 1991, pp. 678-687. (Also, revised version to appear in *Computer Networks & ISDN Systems*, special issue on *Media Access Techniques in High-Speed LANs and MANs*.)

[B2] S. Banerjee and B. Mukherjee, "Incorporating continuation-of-message (COM) information, slot reuse, and fairness in the IEEE 802.6 (DQDB) network," *Computer Networks & ISDN Systems*, special issue on *Metropolitan Area Networks*, vol. 24, pp. 153-169, April 1992.

[B3] Subrata Banerjee, *Optimally-structured high-speed metropolitan area networks with distributed control*, Ph.D. dissertation, Division of Computer Science, University of California, Davis, December 1992 (expected).

C. Integrated Voice-Data Communication

It is anticipated that the high fiber bandwidth should be employed to not only carry data but other services as well such as packetized voice, digital video, etc. We have formulated an efficient mechanism for integrating voice with data. A framed approach is used where a fixed-sized frame, which is repeated periodically, consists of a voice subframe (of variable duration) followed by a data subframe. Our strategy employs a movable boundary architecture with an estimator function for speech, in which the voice subframe size is estimated from the number of voice packets transmitted in the previous frame (by employing local channel feedback). A simple, approximate, and implementable variation of the scheme has also been studied. An additional load-controlled scheme (employing channel feedback) has also been developed for integrated voice-data communication. Real-time video and still-picture integration strategies are being investigated.

Our accomplishments on this topic are documented in the following documents:

[C1] B. Mukherjee and J. S. Meditch, "Integrating voice with the p_i-persistent protocol for unidirectional broadcast bus networks," *IEEE Transactions on Communications*, vol. COM-36, pp. 1287-1295, Dec. 1988.

[C2] B. Mukherjee and S.-K. Kao, "An improved voice-data integration protocol for fiber optic bus networks," *Computer Networks & ISDN Systems*, vol. 25, pp. 103-120, 1992.

[C3] S.-K. Kao and B. Mukherjee, "A load-controlled scheduling scheme for integrated voice-data communication on high-speed LANs/MANs," *Proc., IEEE Globecom 91*, Phoenix, AZ, pp. 466-470, Dec. 1991.

[C4] B. Mukherjee, "Integrated voice-data communication over high-speed fiber optic networks," *IEEE Computer*, vol. 24, no. 2, pp. 49-58, Feb. 1991.

[C5] Shao-kong Kao, *Voice, Video, and Data Integration on High-Speed Fiber Optic Bus Networks*, Ph.D. dissertation, Division of Computer Science, University of California, Davis, March 1993 (expected). (This dissertation is not yet ready, and it has not been included in the enclosed set of papers.)

D. Techniques for Modeling High-Speed MANs

Analytical techniques have been formulated to predict the performance of the networks and protocols that are being developed. Exact analytical models of the entire system are formulated as multidimensional Markov chains. Approximate analytical models, which are faster to solve, are developed by applying queueing theoretic arguments to individual network stations and then by employing an independence assumption to capture the coupling between stations.

The corresponding publications are:

[D1] B. Mukherjee and S. Banerjee, "Alternative strategies for fairness in and an analytical model of DQDB networks," *Proc., IEEE INFOCOM '91*, Bal Harbour, FL, April 1991, pp. 879-888. (Also, revised version to appear in *IEEE Transactions on Computers*.) (Same as A6.)

[D2] Subrata Banerjee, *Optimally-structured high-speed metropolitan area networks with distributed control*, Ph.D. dissertation, Division of Computer Science, University of California, Davis, December 1992 (expected). (Same as B3.)

E. Initiation of Research on Third-Generation (Lightwave) Networks

As part of this project, we also initiated research on the *third* generation of LANs/MANs. The goal is to exploit the capabilities of emerging lightwave technology, viz. dense wavelength division multiplexing (WDM) and tunable optical transmitters and receivers in order to design a true (local) lightwave network (also called an Optical Gigabit LAN). Research on optical devices indicate that the fiber's low-loss region can be exploited so that a single optical medium can carry an aggregate information at approximately 25-30 terahertz (THz). Dense wavelength division multiplexing (WDM) and tunable optical transceiver subtechnologies are also emerging so that this huge optical bandwidth can be carved up into smaller-capacity channels, each of which can operate parallelly at peak end-user (electronic processing) speeds of a few Gbps. The challenge is to develop the networking technology that can exploit the above capabilities of lightwave technology, support parallelism and concurrency, and provide Gbps connections to each of a large number of end-users.

Our approaches to the design and development of such Optical Gigabit LANs exploit the broadcast-and-select property of WDM lightwave networks in which all of the inputs from various nodes are combined in a star coupler and the mixed optical information is broadcast to all outputs. New architectures are being examined for reconfigurable multihop networks. Efficient protocols are also being studied for single-hop communication. Research on the photonic implementation of second generation LANs (viz. the IEEE 802.6 and FDDI networks) has been conducted, and some early results on the photonic implementation of the IEEE 802.6 network have been obtained.

Our contributions on this topic can be found in the following publications:

[E1] B. Mukherjee, "WDM-Based Local Lightwave Networks – Part I: Single-Hop Systems," *IEEE Network*, vol. 6, no. 3, pp. 12-27, May 1992.

[E2] B. Mukherjee, "WDM-Based Local Lightwave Networks – Part II: Multihop Systems," *IEEE Network*, vol. 6, no. 4, pp. 20-32, July 1992.

[E3] S. Banerjee, B. Mukherjee, and D. Sarkar, "Heuristic algorithms for constructing near-optimal structures of linear multihop lightwave networks," *Proc., IEEE Infocom 92*, Florence, Italy, pp. 671-680, May 1992. (Also, revised version to appear in *IEEE Transactions on Communications.*)

[E4] F. Jia and B. Mukherjee, "The receiver collision avoidance (RCA) protocol for a single-hop WDM local lightwave network," *Proc., Intl. Conf. on Communications (ICC 92)*, Chicago, IL, pp. 6-10, June 1992.

[E5] S. Banerjee and B. Mukherjee, "An efficient and fair probabilistic scheduling protocol for a multichannel lightwave network," *Proc., Intl. Conf. on Communications (ICC 92)*, Chicago, IL, pp. 1115-1119, June 1992.

[E6] S. Banerjee and B. Mukherjee, "Optimized ShuffleNet Configurations using WDM Channels," *Technical Digest, 1992 IEEE Summer Topical Meetings on Optical Multiple Access Networks*, Santa Barbara, CA, pp. 39-40, Aug. 1992.

[E7] F. Jia and B. Mukherjee, "A Scalable Reservation-Based Single-Hop WDM Lightwave Network," *Technical Digest, 1992 IEEE Summer Topical Meetings on Optical Multiple Access Networks*, Santa Barbara, CA, pp. 65-66, Aug. 1992.

[E8] F. Jia and B. Mukherjee, "Performance analysis of a generalized receiver collision avoidance (RCA) protocol for single-hop WDM local lightwave networks, *Proc., SPIE OE/FIBERS '92*, Boston, MA, Sept. 1992.

[E9] B. Mukherjee and F. Jia, "Bimodal Throughput, Nonmonotonic Delay, Optimal Bandwidth Dimensioning, and Analysis of Receiver Collisions in A Single-Hop WDM Local Lightwave Network," *Proc., IEEE Globecom '92*, Orlando, FL, Dec. 1992 (to appear).

[E10] B. Mukherjee, "Protocols for optical multiple-access networks," *Technical Digest, Optical Fiber Communications Conference (OFC 93)*, San Jose, CA, Feb. 1993, to appear (Invited Paper).

[E11] S. Banerjee, J. Iness, and B. Mukherjee, "New modular architectures for regular multihop lightwave networks," *Technical Digest, Optical Fiber Communications Conference (OFC 93)*, San Jose, CA, Feb. 1993, to appear.

[E12] Subrata Banerjee, *Optimally-structured high-speed metropolitan area networks with distributed control*, Ph.D. dissertation, Division of Computer Science, University of California, Davis, December 1992 (expected). (Same as B3 and D2.)

[E13] Feiling Jia, *Design and analysis of single-hop WDM local lightwave networks*, Ph.D. dissertation, Division of Computer Science, University of California, Davis, July 1993 (expected). (This dissertation is not yet ready, and it has not been included in the enclosed set of papers.)